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Regional Earth System prediction: a decision-making tool for sustainability?

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While the IPCC will continue to lead Earth System projections for global issues such as greenhouse gas levels and global temperature increase, high-resolution regional Earth System predictions will be crucial for producing effective decision-making tools for day-to-day, sustainable Earth System management and adaptive management of resources. Regional Earth System predictions and projections at the order of a few meters resolution from days to decades must be validated and provide uncertainties and skill scores to be usable. While the task is daunting, it would be criminally negligent of the global human not to embark on this task immediately. The observational needs for the integrated natural-human system for the regional Earth System are distinct from the global needs even though there are many overlaps. The process understanding of the Earth System at the micro scale can be translated into predictive understanding and skillful predictions for sustainable management by merging these observations with Earth System models to go from global scale predictions and projections to regional environmental manifestations and mechanistic depiction of human interactions with the Earth System and exploitation of its resources. Regional Earth System monitoring and predictions thus will continuously take the pulse of the planet to prescribe appropriate actions for participatory decision-making for sustainable and adaptive management of the Earth System and to avoid catastrophic domains of potential outcomes.

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Defining the Earth System

The main objective of this paper is to highlight the potential role for regional Earth System prediction and projection as the main decision-making tool for sustainable management of the Earth System. Prediction in this context refers to forecasts for time-scales of days to seasons, while projection implies model depictions at decadal to longer time-scales including anthropogenic time-scales. Prediction and projection are intended to carry an intrinsic sense of closer correspondence to reality in the former versus a larger uncertainty in the latter.

As intuitive and common as the phrase Earth System may appear, a universally acceptable definition is neither intuitive nor common. Schellnhuber [1,2••] has led the efforts to provide the overarching definition; the Earth System is being composed of the ecosphere and the anthroposphere. The ecosphere here is the geosphere–biosphere complex and includes the more well-known components such as the ocean, atmosphere, and cryosphere along with the biosphere, whereas the anthroposphere puts man on that ignoble pedestal from where he appears to be watching the consequences of his actions [3]. We can live with this definition for the sake of proceeding to our main goal, viz., Earth System prediction and sustainability. A dauntingly comprehensive piping diagram for the Earth System, the now well-known Bretherton diagram is presented by Schellnhuber [2••] but integrating humans into the Earth System has become much more urgent since the original incarnation of this diagram by Fisher [4].

Sustainability is another concept that is intuitive and yet weighty. Simply put, it is the ability of one generation to use the resources without jeopardizing the ability of the future generations to access the same resources [5]. A mathematical definition of sustainability would require the local rate of change, for all the resources by all organisms would be zero [6]. Needless to say, as elegant as these definitions are, implementation or quantification of sustainability would be anything but simple. The most suitable and convenient definition in the context of Earth System prediction is to consider sustainability as an adaptive management with participatory decision-making and learning-by-doing being the mode of operation to strive for global stewardship [7,8].

Does the sustainable use of the Earth System mean human control of the Earth System? Schellnhuber [1] offers a few paradigms for such a control, at least to avoid the catastrophic domains where human existence is possible but subsistence will be miserable. He does offer a prioritized list to achieve sustainable development, as optimization (achieving the best Earth System performance), stabilization (achieve a desirable Earth System state), and pessimization (simply manage to avoid the worst Earth System states). The caveat of course is that putting these paradigms into operation via the Earth System models is highly nontrivial but the task of avoiding catastrophes cannot be abandoned [1,9]. As monumental a task as it is to provide useful and usable Earth System prediction with validation, uncertainties, and skill assessment, not attempting to build viable decision-making tools would be criminally negligent of the global human.

Modeling the Earth System

Schellnhuber [1] offers a conceptual model for the Earth System and delivers the sobering possibility that even if we avoid the runaway warming or the runaway cooling and keep ourselves away from the Martian and Venusian regimes, the catastrophic domains that are suitable for human existence but below the level with minimal quality of life, are still in the realm of possibilities and there will be certain parts of the range of solutions that may be desirable but simply inaccessible. For example, we may have already committed to a level of warming and sea level rise [10] that may not be mitigated even by the metaphysical subcomponent of the human factor that Schellnhuber [2••] refers to as the 'global subject', an approximate analog being the IPCC process.

I will explore the concept of Earth System prediction with that sobering background even though some skepticism persists about the validity and usefulness of such a prediction. The concept of Earth System modeling and prediction evolved on the shoulders of some giants that led the pioneering efforts in weather and climate prediction. The legendary attempt by Richardson to use a roomful of humans as a computer to attempt the very first numerical weather prediction (NWP) was truly visionary [11]. Advances in computer technology facilitated many major advances in NWP over the next several decades [12]. Much progress was made in NWP into the 1940s and 1950s mostly based on demands for meteorological information by the militaries [13,14]. A seminal study by Lorenz [15] showed that seemingly insignificant errors in the initial conditions can generate large errors in prediction with the so-called butterfly effect or chaos [15,16] that made dynamical predictions of weather beyond a few days unattainable. It would take more than a decade before another seminal work proposed predictability well beyond the few days that weather was predictable to, termed predictability of the second kind based on the role of boundary forcing [16,17]. Climate forecast has taken a complex trajectory compared to weather prediction since climate has many modes of variability such as the monsoons and the El Niño-Southern Oscillation (ENSO), with their own spatio-temporal scales and predictabilities [18,19••,20]. The envelope of climate prediction continues to be pushed with new advances in decadal time-scale predictions [21]. Although predictions generally refer to short lead-times of days to seasons, the terminology is being extended to decadal time-scales in recent literature [21].

The natural evolution of climate modeling toward Earth System models was motivated by some of the most fascinating Earth System feedbacks, such as the potential role of biophysical feedbacks on droughts over Sahara [22]. The evolution of the coupled ocean–atmosphere models was accompanied by the development of other Earth System component models [23] and initiated the drive to consider the feedbacks between the physical climate system and the terrestrial and marine biogeochemistry and ecosystems [24,25]. The early Earth System models represented these processes in a simplified framework where choices had to be made between the details, numbers, and complexities of processes being modeled [26]. Another major new direction of development of relevance to Earth System prediction was the early dynamic downscaling to regional scales [27,28]. The formation of the Intergovernmental Panel for Climate Change (IPCC) by the United Nations and the World Meteorological Organization in 1988 was the quintessential 2nd Copernican Revolution; the process of climate projections and its purview in terms of socioeconomic and policy aspect of climate change, its mitigation and adaptation to climate change in the IPCC models continue to expand. It is not just the complexity and the details of the models that are increasing but also the resolution of the global models employed in IPCC projections have monotonically increased [29]. This should facilitate dynamic downscaling to regional scales and extend the climate projections into Earth System projections.

Even as the spatial resolutions of the Earth System models improve with each IPCC assessment, they remain at order 10 km and are expected to remain at those scales for many years if not decades. It is evident that adaptive management of resources demand Earth System information at the order of 1 km or less and the only way to reach these goals is via dynamical and statistical downscaling. Dynamical downscaling through regional climate modeling has now been applied to various Earth System issues such as human health, agriculture, and water resources [30–32]. The intrinsic nonlinearities in the physical climate system are made more conducive to emergent solutions when the Earth System feedbacks are included [33,34]. Regional Earth System is admittedly counter-intuitive but the Earth System is indeed a system of systems and the regional specificity of the ecosphere and the anthroposphere must be seen as an integrated global Earth System with nested regional Earth Systems with their own idiosyncrasies. The concept is parallel to ecosystem biomes where the ecosphere and the anthroposphere are congruous at regional scales with global connectivity. The grand challenge is to use these model constructs to generate information at all required scales for sustainable Earth System management.

Earth System prediction

The need to integrate humans and human influence on the Earth System was emphasized by the Amsterdam Declaration on Climate Change at the first Global Change Open Science conference held in Amsterdam in 2001. One response was an attempt to strengthen the integration across environmental and developmental issues and the natural and social sciences. While there is no unique approach to an Earth System modeling framework, the International Geosphere Biosphere Project (IGBP), DIVERSITAS, the World Climate Research Program (WCRP), and the International Human Dimensions Program (IHDP) have created the new Earth System Science Partnership focused on energy and carbon cycles, food systems, water resources, and human health as the most critical issues for human well-being (http://www.essp.org). Along these lines, the WCRP launched a new strategic framework for Coordinated Observation and Prediction of the Earth System (COPES), which lists the following as one of its aims; to facilitate analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit, and value to society (http://wcrp.ipsl.jussieu.fr/). IGBP's focus is on the interactions between biological, chemical and physical processes and interactions with human systems, and the IGBP has a stated vision of providing scientific knowledge for improving sustainability of the Earth System. Both WCRP and IGBP strive to model the Earth System and are clear manifestations of the 2nd Copernican Revolution and the human attempts to integrate themselves into the Earth System.

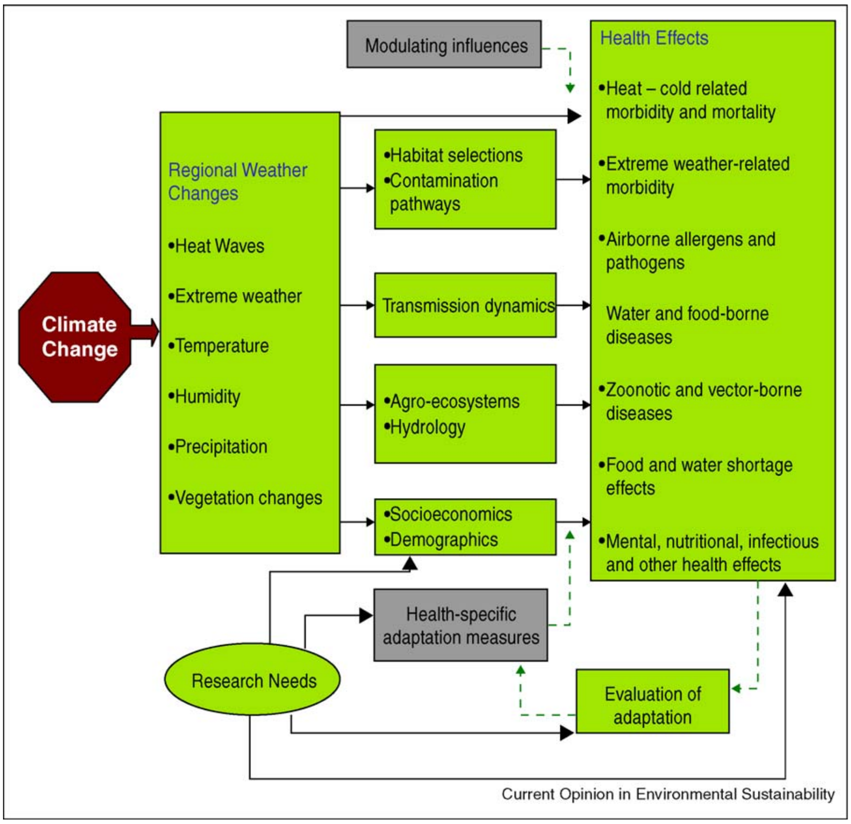
Any realistic Earth System prediction must immediately focus on quantitative forecasts for decision-making, keeping in mind the holistic principles of sustainable management of the future trajectories of the Earth System evolution [2••]. The enormity of the task is daunting considering the complexity of the interactions and feedbacks between humans and natural systems with the coupling dependent on space, time, and organizational structures [35]. The surprises and thresholds or the resilience and time-lags of the nonlinear dynamics of these interactions can easily be missed by the separation of the analysis into social or natural sciences. It is the same artificial dichotomy between economic and environmental policies that can lead to unintended and irreversible consequences and the loss of resilience in the Earth System [36•]. The systems approach to avoid these artificial disciplinary boundaries must also place environmental prediction at the center of sustainability and recognize the need to focus on the science of human interactions with the environment [37,38], and the intimate and deepening interplay between the environment, food, human health, national security, economy, and social justice [35,36•,37,38].

The most well-known mode of climate variability, viz., the ENSO has a similar global reach and does offer an excellent analogy for Earth System interactions and a set of predictable targets with applications from agriculture to fisheries to human health [39•]. Combined with the evidence for some decadal time-scale predictability [21], the two time-scales of Earth System prediction, including human interactions and feedbacks, evolve naturally; a shorter time-scale from days to seasons for adaptive management of natural resources such as water and energy, and human needs such as health and food security. The longer time-scale of years to decades and longer, transition us from climate variability to the realm of climate change where the separation of cause and effect tends to be significantly wider. The need for the spatio-temporal resolution of the information for adaptive management at shorter time-scales is also significantly higher than for participatory decision-making at climate change time-scales, with the latter being more of a guidance to adaptive policy decisions [40,41•].

The question of uncertainties in Earth System predictions at both short and long time-scales are crucial with the former requiring quantitative measures of skill in addition, whereas projections of future trajectories of the Earth System at longer time-scales will need to offer a more solid understanding of the known unknowns or irreducible uncertainties [2••,41•,42]. The short-term Earth System predictions must focus on the finer spatial scales at which the faster time-scale Earth System interactions and human responses occur while the longer time-scale projections must develop a range of options for the integration of humans and their actions, not only to avoid catastrophic domains of climate change but also to seek 'safe and benign' solutions [43•]. It is evident that a spectrum of Earth System models with interactive human component is required to address the global Earth System governance including simulations of past climates to offer a rear-view mirror for future scenarios of adaptive management [26,41•]. Since the Anthropocene is potentially headed into a realm not seen before [3,9], global Earth System models and the monitoring system will be the tools for spanning the phase-space of adaptive and participatory policies to steer the Earth System toward that continuous transition to sustainability [44], where hard policy decisions will be made based on soft scientific input with numerous ambiguities [7,42].

A much more quantifiable success can be achieved at regional scales and shorter lead-times (days to seasons), in high-resolution regional Earth System models with the boundary conditions provided by the global Earth System models. The advantages of local and regional understanding of natural-human system interactions or the 'place-based' Earth System predictions and decision-making are evident in a number of success stories [43•]. I present one specific application of a regional Earth System prediction

Figure 1



Schematic of linkages from climate change driver to human health to illustrate the need for interdisciplinary research and a comprehensive and integrated approach to achieve Earth System prediction and projection for human health (modified from Ref. [46]). Similar pathways exist for other resource managements.

system to illustrate the enormity of the task and to reiterate the need for interdisciplinary and integrated approach to the research and training necessary for accomplishing the goal of adaptive management and sustainability [40].

Earth System prediction for human health: What do we need to make it a reality?

A prime example of a practical application of direct relevance, benefit, and value to society is environmental information for human health which is intricately intertwined with the environment, water, and agriculture [45]. The knowledge that the environment affects human health goes all the way back to Hippocrates [46]. The traditional approach or the old paradigm of climate prediction for human health tends to find correlations between climatic variables and disease incidences, outbreaks, or indicators that are precursors to an outbreak [47]. The examples range from heat and cold wave related mortalities, cholera, malaria, Rift Valley fever, dengue fever, meningitis, and so on [48•,49–53]. How useful is it to simply use statistical relations if climate change is expected to alter the environmental conditions and population growth may affect the transmission dynamics? The impacts of global change are clearly manifest in global indicators such as temperature and sea level rise but the impacts on humans are often associated with local changes in weather, ecology, water resources, etc. A succinct way to illustrate the linkages from climate change to human health with the intermediate steps of microhabitat selection by the relevant microbes, transmission dynamics, socioeconomics, and the need for research and adaptation measures, is shown in Figure 1 which is modified from [54].

It is imperative to drive the Earth System prediction efforts for human health with the clear understanding that the ultimate reliability and success of a prediction system will depend on filling the gaps in mechanistic linkages from changes in climate to human health. While the ENSO paradigm has led to several successes in using direct correlations between climate variables and disease outbreaks including some early warning or forecast systems [47], climatic variables such as temperature, precipitation, humidity, and the frequency of their occurrences via changes in extreme events are all expected to affect human health through associated changes in ecological responses and transmission dynamics with a whole host of socioeconomic and demographic factors exerting many complex modulating influences [54,55]. The role of the microbial contamination pathways can be brought to focus by considering the example of human infections by toxic algal blooms in the marine or lacustrine environment. The algae or the microbes in these water-bodies that are toxic to humans strive to exploit a microhabitat for their own competitive edge and do not attempt to genetically hone their toxicity or virulence for humans since infected persons do not necessarily return to the water-body to provide feedback to the microbes [56]. This instantly points to the shortcomings in using a climatic habitat index to forecast the incidences or toxicity of such harmful algal blooms or pathogen levels without also considering the genetic, chemical, and biological factors, the microbial contamination pathways, human behavior, and exposure. The levels of most of the harmful algae and pathogens are related to human activity such as agriculture, waste water treatments, and land use change [57–60]. Theoretical and empirical process understanding from vastly different fields such as hydrology, watershed and water resource managements, agriculture and crop modeling, ecology, population dynamics and human behavior, have to be translated into predictive understanding to construct forecast models. More importantly, these disparate pieces have to be integrated into Earth System models, especially in the high-resolution regional Earth System models [30].

Technological innovations must drive creations of global digital libraries of air and water quality including the pathogens and their genetic information and instrumentation so that decision-makers on the ground carrying detectors such as hand-held bacterial counters or optimally distributed web of sensors that monitor environmental factors and bacterial levels can instantly validate the Earth System forecasts by comparing local air or water quality against the digital library [56]. Research and development for the human health system must bring new advances in computational social science to capture transmission dynamics and human movement and behavior [61,62] and to combine theoretical models and analytical tools and detectors to drive new directions in the research and implementation of environmental health prediction and protection [63–65]. Each component of the Earth System must consider alternate or newer paradigms to be able to use evolving Earth System predictions for providing more precise and usable feedbacks to the prediction system to lay the foundation for adaptive management and to capture emergent solutions. For example, in addition to detailed modeling of public health via computational social science and computational toxicology, more systems thinking must be brought to bear on public health practice [66,67]. The prediction models must be effective decision-making tools for specific mitigation and adaptation measures and response training such that the evaluation of the impacts of policy and management decisions in modulating climate change, regional weather changes, resource distributions and allocations, population growth and movements and the associated cascades to human health must be a continuous feedback to the Earth System models.

The need for sustained observations for continuously validating and assessing uncertainties in our Earth System models will need global and regional scale Earth System monitoring such as the Global Earth Observing System of Systems (GEOSS), being co-coordinated by the Group on Earth Observations (GEO; http://www.earthobservations.org/index.html). The stated vision for GEOSS is to realize a future wherein decisions and actions for the benefit of human kind are informed by coordinated, comprehensive, and sustained Earth observations and information. The GEO plan defines nine societal benefit areas of disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity which is nearly comprehensive enough for the monitoring and nowcast–forecast vision of Earth System prediction models.

Regional Earth System prediction: a prototype

A nascent but quite a comprehensive effort on regional Earth System prediction is underway within the Earth System Science Interdisciplinary Center (http://essic.umd.edu) of the University of Maryland with dynamic downscaling of the seasonal to interannual climate forecasts and IPCC projections for the Chesapeake watershed with a regional atmosphere, watershed, and a regional ocean model. Routine forecasts of the Chesapeake airshed, watershed, and the estuary include seasonal predictions and decadal projections of such linked products as pathogens, harmful algal blooms, sea nettles, water and air quality, fisheries, dissolved oxygen, inundation, and storm-surge. A prototype decision-making tool has been developed where the user can change the land use types (urban, wetlands, different crops, forests, livable habitat, and smart growth concepts) and choose the time period of interest from the past, present, or the future to compute the nutrient loading in the Chesapeake Bay, dissolved oxygen levels, harmful algal blooms, sea nettles, fisheries habitat suitability, etc. The tool is being made fully three-dimensional with the Google Earth and Google Ocean concepts to provide an integrated assessment and education tool for terrestrial and marine ecosystems and other resources. A unique, new approach is being attempted where specific users are being directly given the Earth System forecasts and the flow of information in their decision-making process is being monitored to obtain quantitative feedbacks. A larger context for this prototype effort is provided by a program called Climate Information: Responding to User Needs (CIRUN) which organizes workshops of users varying from agricultural to insurance sectors to national security (http://climateneeds.umd.edu), as a pioneering effort to drive a demand-pull for specific Earth System information instead of the old paradigm of supply-push where a vast number of model products are placed on the loading-dock hoping for users to pick them up, simply because modelers think they are useful [4]. The early returns on the use of our sea nettle forecasts by the recreational boaters are quite encouraging but we eagerly await the feedback from the watermen, river keepers, forest conservators, etc.

One can expect that such regional Earth System models with direct user-feedbacks will only become more comprehensive, complete and mechanistic, and more interactive and realistic, such that they will serve as the quantitative decision-making tools for sustainable management of the Earth System. With computational resources, the models can easily be run at a scale of a few hundred meters and with the comprehensive observational networks, further statistical downscaling can be accomplished down to a few meters to produce predictive, pre-emptive, and personalized Earth System information not only for human health but also for water and agriculture, transportation and energy, land use, air and water quality management, and sustainable use of the Earth System. Note that achieving such resolutions in global Earth System models is not possible in the near-term and even if it could be achieved for the present generation of Earth System models, the goal of modeling microbes to man is most likely to be accomplished in the regional Earth System models. The decision-making tool must serve to answer the analytical, normative, operational, and strategic questions pertaining to the advancement of Earth System Science [5,68].

What are the hurdles for Earth System prediction for sustainability?

Climate forecasts and their applications for decision-making have had many successes [47] but there is hardly a consensus on whether further investments in climate predictions and projections will indeed lead to increased accuracy and reduced uncertainty [42,69,70]. Identifying the shortcomings and uncertainties of the models in known regimes and knowing the vulnerability of the decisions made in response to climate impacts and projections have to work with known techniques to reduce uncertainties in our forecasts and projections [70,71]. New methodologies will be needed for an integrated assessment of the Earth System under climate change such that systemic constraints on the thresholds, switches, or choke points in the system [33], along with the multitude of normative constraints such as the carrying capacity of the Earth [36•] are answered within the context of policy decisions and sustainable Earth System management. Novel approaches such as the tolerable windows are being devised to address some of these issues of integrated assessment of climate change [72] and quantitative approaches to normative questions such as the value of the environment to human well-being [73].

Bigger challenges will be to ensure that the dissemination of information does not continue or exacerbate pre-existing inequities [74•,75•] and to identify end-user groups that face adverse socioeconomic impacts of climate variability and change [76,77]. Just as important would be to effectively communicate the uncertainties in the forecasts and the underlying assumptions that may limit the applicability of the forecasts [78,79].

Concluding thoughts

As noted by others, it is often good to say the old truth again [8] and sustainability is an issue that needs to be discussed as often as possible in as many contexts as necessary. What I have suggested here is not necessarily

Figure 2

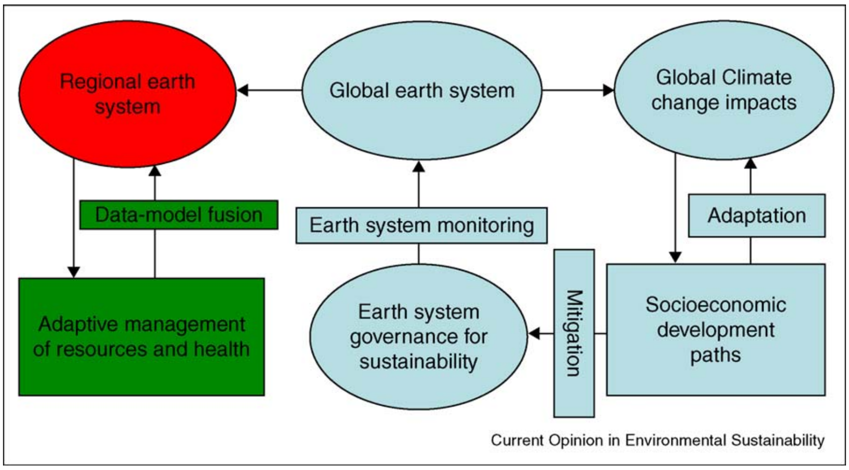


Illustration of Earth System prediction and projection for global Earth System governance and region adaptive management and participatory decision-making. Earth System observations at global and regional scales are needed for model-data blending to accomplish high-resolution regional downscaling and for monitoring for environmental and sustainability indicators.

new except to suggest that Earth System prediction be considered at two distinct time and space scales in addition to the use of a spectrum of models with varying complexity. The IPCC framework for integrated modeling focuses on finding future evolution of the Anthropocene by coupling alternative socioeconomic development options to Earth System changes with adaptation and mitigation strategies providing feedbacks [41•]. A modified version of the framework is presented in Figure 2 where the global Earth System models with the macroscopic monitoring [43•] providing the tools for the global subject [2••] to address the Earth System governance issues such as emissions, biodiversity, and the general issues of standardization and transition toward sustainability at time-scales of years to decades. The additional tool being advocated here is to have a suite of regional Earth System models with model-data blending for better initialization for prediction at days to seasons at resolutions of order meters to produce predictive, personalized, and pre-emptive environmental package for adaptive management and participatory decision-making for human needs. The question of uncertainties cannot be used as an excuse for inaction anymore since the focus has to be on immediately implementing prediction systems and observational networks for sustainable resource management on a day-to-day basis.

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Chris Brown of NOAA read an earlier version of the manuscript. The manuscript was notably improved by the detailed comments of the editor, Rik Leemans for which I am deeply indebted.

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- •• of outstanding interest

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